AN OVERVIEW OF MODAL-BASED DAMAGE IDENTIFICATION METHODS

Charles R. Farrar and Scott W. Doebling
Engineering Analysis Group
Los Alamos National Laboratory
Los Alamos, NM

ABSTRACT

This paper provides an overview of methods that examine changes in measured vibration response to detect, locate, and characterize damage in structural and mechanical systems. The basic idea behind this technology is that modal parameters (notably frequencies, mode shapes, and modal damping) are functions of the physical properties of the structure (mass, damping, and stiffness). Therefore, changes in the physical properties will cause detectable changes in the modal properties. The motivation for the development of this technology is first provided. The methods are then categorized according to various criteria such as the level of damage detection provided, model-based vs. non-model-based methods and linear vs. nonlinear methods. This overview is limited to methods that can be adapted to a wide range of structures (i.e., are not dependent on a particular assumed model form for the system such as beam-bending behavior and methods and that are not based on updating finite element models). Next, the methods are described in general terms including difficulties associated with their implementation and their fidelity. Past, current and future-planned applications of this technology to

actual engineering systems are summarized. The paper concludes with a discussion of critical issues for future research in the area of modal-based damage identification.

INTRODUCTION

The interest in the ability to monitor a structure and detect damage at the earliest possible stage is pervasive throughout the civil, mechanical and aerospace engineering communities. Current damage-detection methods are either visual or localized experimental methods such as acoustic or ultrasonic methods, magnetic field methods, radiograph, eddy-current methods and thermal field methods (Doherty [1]). All of these experimental techniques require that the vicinity of the damage is known *a priori* and that the portion of the structure being inspected is readily accessible. Subjected to these limitations, these experimental methods can detect damage on or near the surface of the structure. The need for additional global damage detection methods that can be applied to complex structures has led to the development and continued research of methods that examine changes in the vibration characteristics of the structure.

The increase in research activity regarding vibration-based damage detection is the result of the coupling between many factors that can be generally categorized as spectacular failures resulting in loss of life that have received ample news media coverage, economic concerns, and recent technical advancements. Failures such as the in-flight loss of the exterior skin on an Aloha Airlines flight in Hawaii and the resulting media coverage focus the public's attention on the need for testing, monitoring, and evaluation to ensure the safety of structures and mechanical systems used by the public. The publics' concerns, in turn, focuses politicians attention on this issue and, hence, industry and regulatory agencies are influenced to provide the funding resources necessary for the development and advancement of this technology. The current state of our infrastructure and the economics associated with its repair have also been motivating factors for the development of methods that can be used to detect the onset of damage or deterioration at the earliest possible stage.

Finally, increases in cost-effective computing memory and speed, advances in sensors including non-contact and remotely monitored sensors, adaptation and advancements of the finite element method, adaptation of modal testing (most recently by the civil engineering community), and development of nonlinear system identification methods all represent technical advancements that have contributed to advancements in modal-based damage detection.

It is the authors' speculation that damage or fault detection, as determined by changes in the dynamic properties or response of systems has been practiced in a qualitative manner, using acoustic techniques, since modern man has used tools. More recently, this subject has received considerable attention in the technical literature where there have been a concerted effort to develop a firmer mathematical and physical foundation for this technology. However, the basic idea remains that commonly measured modal parameters (notably frequencies, mode shapes, and modal damping) are functions of the physical properties of the structure (mass, damping, and stiffness). Therefore, changes in the physical properties, such as reductions in stiffness resulting from the onset of cracks or loosening of a connection, will cause detectable changes in these modal properties. Because changes in modal properties or properties derived from these quantities are being used as indicators of damage, **the process of modal-based damage detection eventually reduces to some form of a pattern recognition problem.**

The idea that changes in vibration characteristics can provide information regarding damage in a structure is very intuitive and one may ask the question: Why has this technology taken such a long time to be formally and generally adopted by the modern engineering community? The answer is that there are several confounding factors making modal-based damage identification difficult to implement in practice. **First, standard modal properties represent a form of data compression**. Modal properties are estimated experimentally from measured response-time histories. A typical time-history may have 1024 data points, and if measurements are made at 100 points, there are 102,400 pieces of information regarding the current state of the structure. For this discussion the additional data typically obtained from averaging will not be considered as providing supplemental data, but rather improving the accuracy of 100 measurements. Through system identification procedures commonly referred to as experimental modal analysis (Ewins [2]) this volume of data is reduced to some number of resonant frequencies, mode shapes and modal damping values. This data compression is done because the modal quantities are easier to visualize, physically interpret, and interpret in terms of standard mathematical modeling of vibrating systems than are the actual time-history measurements. If twenty real modes are identified, then the 102,400 pieces of information will have been reduced to 2020-2040 pieces of information (20 modes made up of 100 amplitudes values (99 if one measurement is used to record the input), 20 resonant frequencies and 20 modal damping values).

Intuitively, information about the current state of the structure must be lost in this data reduction and system identification process. The loss of information occurs primarily from the fact that for a linear system the modal properties are independent of the excitation signal characteristics (amplitude and frequency content) and the location of the excitation whereas the time histories are not. In addition, if the input excites response at frequencies greater than those that can be resolved with the specified data sampling parameters, the identified modes will not provide any information regarding the higher frequency response characteristics of the structure that are contributing to the measured time-history responses. Within the measured frequency range of response it is often difficult to identify all the modes contributing to the measured response because of coupling between the modes that are closely spaced in frequency. This difficulty is observed more commonly at the higher frequency portions of the spectrum where the modal density is typically greater. Also, the introduction of bias (or systematic) errors, such as those that arise from windowing of the data and those that arise from changing environmental conditions during the test, will tend to make the identified modal parameters less representative of the true dynamic properties of the structure.

Damage typically is a local phenomenon. Local response is captured by higher frequency modes whereas lower frequency modes tend to capture the global response of the structure and are less sensitive to local changes in a structure. From a testing standpoint it is more difficult to excite the higher frequency response of a structure as more energy is required to produce measurable response at these higher frequencies than at the lower frequencies. These factors coupled with the loss of information resulting from the necessary reduction of time-history measurements to modal properties add difficulties to the process of modal-based damage identification and contribute to the current state where this technology is still in the research arena with only limited standard practice by the engineering community.

A logical question then is: Why not examine the time-histories directly for indications of damage? The answer is that, despite the difficulties associated with damage detection based on changes in modal properties, it is even more difficult to examine response-time histories directly, identify that damage has occurred based on the changes in patterns of these time histories, and relate these changes to physical changes in the structure. If excitation sources change and/or environmental conditions change this process becomes even more difficult. However, it should be pointed out that when the system response changes from linear to nonlinear and the location of the damage is known *a priori* (as is the case with loosening of bearings on rotating machinery), time histories alone (actually their frequency domain power spectrum) are sufficient to identify damage and represent one of the most widely practiced forms of vibration-based damage identification (Wowk [3]).

Notwithstanding the difficulties discussed above, advances in modal-based damage detection over the last 20-30 years have produced new methods of examining vibration data for indications of structural damage. These methods are seeing more widespread applications. One of the most prominent examples of this recent application is NASA's space shuttle modal inspection system (Hunt, et al. [4]). Because of difficulties accessing the exterior surface caused by the thermal protective system, a modal-based damage detection system was developed. This system has identified damage that would have alluded traditional NDT methods because of inaccessibility to the damaged components and has been adopted as a standard inspection tool for the shuttles.

It is the intent of this paper to provide an overview of these recent advances in modal-based damage detection. This paper is based on a previous detailed review of the modal-based damage detection literature (Doebling, et al. [5]). As mentioned previously, the field of damage identification is very broad and encompasses both local and global methods. This paper will be limited to global methods that are used to infer damage from changes in vibration characteristics of the structure. Many different issues are critical to the success of using the mechanical vibration characteristics of a structure for damage identification and health monitoring. Among the important issues are excitation and measurement considerations, including the selection of the type and location of sensors, and the type and location of the excitations. Another important topic is signal processing, which includes such methods as Fourier analysis, time-frequency analysis and wavelet analysis. In this paper, these peripheral issues will not be directly addressed. The scope of this paper will be limited to the methods that use changes in modal properties (i.e. modal frequencies, modal damping ratios, and mode shapes) to infer changes in mechanical properties, and the application of these methods to engineering problems. Methods that require a finite element model of the structure are not included in this discussion.

CLASSIFICATION OF DAMAGE AND DAMAGE ID METHODS

The effects of damage on a structure can be classified as linear or nonlinear. A linear damage situation is defined as the case when the initially linear-elastic structure remains linear-elastic after damage. The changes in modal properties are a result of changes in the geometry and/or the material properties of the structure, but the structural response can still be modeled using linear equations of motion. Linear methods can be further classified as model-based and non-model-based. Model-based methods assume that the monitored structure responds in some predetermined manner such as the response described by Euler-Bernoulli beam theory.

Nonlinear damage is defined as the case when the initially linear-elastic structure behaves in a nonlinear manner after the damage has been introduced. One example of nonlinear damage is the formation of a fatigue crack that subsequently opens and closes under the normal operating vibration environment. Other examples include loose connections that rattle and nonlinear material behavior such as that exhibited by foam rubber. The majority of the studies reported in the technical literature address only the problem of linear damage detection.

Another classification system for damage-identification methods, defines four levels of damage identification, as follows (Rytter [6]):

- Level 1: Determination that damage is present in the structure
- Level 2: Level 1 plus determination of the geometric location of the damage
- Level 3: Level 2 plus quantification of the severity of the damage
- Level 4: Level 3 plus prediction of the remaining service life of the structure

To date, modal-based damage identification methods that do not make use of some structural model primarily provide Level 1 and Level 2 damage identification. When modal-based methods are coupled with a structural model, Level 3 damage detection can be obtained in some cases. Level 4 prediction is generally associated with the fields of fracture mechanics, fatigue life analysis, or structural design assessment and, as such, is not addressed in this paper.

EARLY DIFFICULTIES

Most of the modern developments in modal based damage detection stem from studies performed in the 1970s and early 1980s by the offshore oil industry (Vandiver [7,8], Begg [9], Loland and Dodds [10], Wojnarowski [11], Coppolino and Rubin [12], Duggan et al. [13], Kenley and Dodds [14], Crohas and Lepert [15], Nataraja [16], and Whittome and Dodds [17]). However, these studies were less than successful. Instead, it was found that above-water-line measurements could provide information about resonant frequencies only. Environmental conditions such as marine growth that adds significant mass to the structure, equipment noise and changing mass associated with changing fluid tank levels corrupted the data. These tests also identified uniqueness issues associated with the damage prediction if only resonant frequencies are used. Because of the lack of success, the oil industry abandoned this technology in the mid 1980s.

DAMAGE DETECTION BASED ON CHANGES IN BASIC MODAL PROPERTIES

The experiences of the offshore oil industry have been repeated by numerous other investigators who have tried to examine changes in basic modal properties. In this context basic modal properties will be defined as resonant frequencies, modal damping, and mode shape vectors.

Frequency Changes

The amount of literature related to damage detection using shifts in resonant frequencies is quite large. The observation that changes in structural properties cause changes in vibration frequencies was the impetus for using modal methods for damage identification and health monitoring. Because of the large amount of literature, not all papers that the authors have reviewed on this subject are included in the reference list of this paper. A more thorough review and reference list can be found in [5]. An effort has been made to include the early work on the subject, some papers representative of the different types of work done in this area, and papers that are considered by the authors to be significant contributions in this area.

It should be noted that frequency shifts have significant practical limitations for applications to the type of structures considered in this review, although ongoing and future work may help resolve these difficulties. The somewhat low sensitivity of frequency shifts to damage requires either very precise measurements or large levels of damage. However, recent studies have shown that resonant frequencies have less statistical variation from random error sources than other modal parameters (Farrar, et al. [18] and Doebling, et al. [19]).

For example, in offshore platforms damage-induced frequency shifts are difficult to distinguish from shifts resulting from increased mass from marine growth. Tests conducted on the I-40 bridge (Farrar, et al., [20]) also demonstrate that frequency shifts are not sensitive indicators of damage. When the cross-sectional stiffness at the center of a main plate girder had been reduced 96.4%, reducing the bending stiffness of the overall bridge cross-section by 21%, no significant reductions in the modal frequencies were observed. Currently, using frequency shifts to detect damage appears to be more practical in applications where such shifts can be measured very precisely in a controlled environment, such as for quality control in manufacturing. As an example, a method known as “resonant ultrasound spectroscopy”, which uses homodyne detectors to make precise sine-sweep frequency measurements, has been used successfully to determine out-of-roundness of ball bearings (Migliori, et al., [21]).

Also, because modal frequencies are a global property of the structure, it is not clear that shifts in this parameter can be used to identify more than the mere existence of damage. In other words, the frequencies generally cannot provide spatial information about structural changes. An exception to this limitation occurs at higher modal frequencies, where the modes are associated with local responses. However, the practical limitations involved with the excitation and extraction of these local modes, caused in part by high modal density, can make them difficult to identify. Multiple frequency shifts can provide spatial information about structural damage because changes in the structure at different locations will cause different combinations of changes in the modal frequencies. However, as pointed out by several authors, there is often an insufficient number of frequencies with significant enough changes to determine the location of the damage uniquely.

The Forward Problem

The forward problem, which usually falls into the category of Level 1 damage identification, consists of calculating frequency shifts from a known type of damage. Typically, the damage is modeled mathematically, then the measured frequencies are compared to the predicted frequencies to determine the damage. This method was used extensively by previously mentioned offshore oil industry investigator

As an example, (Cawley and Adams [22]) give a formulation to detect damage in composite materials from frequency shifts. They start with the ratio between frequency shifts for modes i and j, . A grid of possible damage points is considered, and an error term is constructed that relates the measured frequency shifts to those predicted by a model based on a local stiffness reduction. A number of mode pairs is considered for each potential damage location, and the pair giving the lowest error indicates the location of the damage. The formulation does not account for possible multiple-damage locations. Special consideration is given to the anisotropic behavior of the composite materials.

(Friswell, et al. [23]) present the results of an attempt to identify damage based on a known catalog of likely damage scenarios. The authors presume that an existing model of the structure is highly accurate. Using this model, they computed frequency shifts of the first n modes for both the undamaged structure and all the postulated damage scenarios. Then ratios of all the frequency shifts were calculated. For the candidate structure, the same ratios were computed, and a power-law relation was fit to these two sets of numbers. When the body of data is noise-free, and when the candidate structure lies in the class of assumed damages, the correct type of damage should produce a fit that is a line with unity slope. For all other types of damage the fit will be inexact. The likelihood of damage was keyed on the quality of the fit to each pattern of known damage. Two measures of fit were used: the first was related to the correlation coefficient; the second was a measure of how close the exponent and coefficient were to unity. Both measures were defined on a scale from 0 to 100. It was hypothesized that damage was present when both measures were near 100.

(Gudmundson [24]), (Tracy and Pardoen, [25]), and (Penny, et al. [26]) present other approaches to forward problem.

The Inverse Problem

The inverse problem, which is typically Level 2 or Level 3 damage identification, consists of calculating the damage parameters, e.g., crack length and/or location, from the frequency shifts. (Lifshitz and Rotem [27]) present what may be the first journal article to propose damage detection via vibration measurements. They look at the change in the dynamic moduli, which can be related to the frequency shift, as indicating damage in particle-filled elastomers. The dynamic moduli, which are the slopes of the extensional and rotational stress-strain curves under dynamic loading, are computed for the test articles from a curve-fit of the measured stress-strain relationships at various levels of filling.

(Stubbs and Osegueda, [28,29]) developed a damage detection method using the sensitivity of modal frequency changes that is based on work by (Cawley and Adams [22]). In this method, an error function for the ith mode and pth structural member is computed assuming that only one member is damaged. The member that minimizes this error is determined to be the damaged member. This method is demonstrated to produce more accurate results than their previous method in the case where the number of members is much greater than the number of measured modes. The authors point out that this frequency-change sensitivity method relies on sensitivity matrices that are computed using a FEM. This requirement increases the computational burden of these methods and also increases the dependence on an accurate prior numerical model. To overcome this drawback, (Stubbs, et al. [30]) developed a damage index method, which is presented below.

(Adams, et al. [31]), (Wang and Zhang [32]), (Stubbs, et al. [33]), (Hearn and Testa [34]), (Richardson and Mannan [35]), (Sanders, et al. [36]), (Narkis [37]), (Brincker, et al. [38]), (Balis Crema, et al. [39]), and (Skjaerbaek, et al. [40]) present further examples of inverse methods for examining changes in modal frequencies for indications of damage

MODE SHAPE CHANGES

(West [41]) presents what is possibly the first systematic use of mode shape information for the location of structural damage without the use of a prior FEM. The author uses the modal assurance criteria (MAC) to determine the level of correlation between modes from the test of an undamaged Space Shuttle Orbiter body flap and the modes from the test of the flap after it has been exposed to acoustic loading. The mode shapes are partitioned using various schemes, and the change in MAC across the different partitioning techniques is used to localize the structural damage.

(Fox [42]) shows that single-number measures of mode shape changes such as the MAC are relatively insensitive to damage in a beam with a saw cut. Again this highlights the problem that too much data compression can cause in damage identification. “Node line MAC,” a MAC based on measurement points close to a node point for a particular mode, was found to be a more sensitive indicator of changes in the mode shape caused by damage. Graphical comparisons of relative changes in mode shapes proved to be the best way of detecting the damage location when only resonant frequencies and mode shapes were examined. A simple method of correlating node points—in modes that show relatively little change in resonant frequencies—with the corresponding peak amplitude points—in modes that show large changes in resonant frequencies—was shown to locate the damage. The author also presents a method of scaling the relative changes in mode shape to better identify the location of the damage.

(Mayes [43]) presents a method for model error localization based on mode shape changes known as structural translational and rotational error checking (STRECH). By taking ratios of relative modal displacements, STRECH assess the accuracy of the structural stiffness between two different structural degrees of freedom (DOF). STRECH can be applied to compare the results of a test with an original FEM or to compare the results of two tests.

(Yuen [44]), (Rizos, et al. [45]), (Osegueda, et al. [46]), (Kam and Lee [47]), (Kim, et al. [48]), (Srinivasan and Kot [49]), (Ko, et al. [50]), (Salawu and Williams [51, 52]), (Lam, et al. [53]), and (Salawu [54]) provide examples of other studies that examine changes in mode shapes, primarily through MAC and coordinate MAC (or COMAC) values, to identify damage.

Mode Shape Curvature/Strain Mode Shape Changes

An alternative to using mode shapes to obtain spatial information about sources of vibration changes is using mode shape derivatives, such as curvature. It is first noted that for beams, plates and shells there is a direct relationship between curvature and bending strain. The practical issues of measuring strain directly or computing it from displacements or accelerations are discussed by some researchers.

(Pandey, et al. [55]) demonstrate that absolute changes in mode shape curvature can be a good indicator of damage for the FEM beam structures they consider. The curvature values are computed from the displacement mode shape using the central difference operator.

(Stubbs, et al. [30]) present a method based on the decrease in modal strain energy between two structural DOF, as defined by the curvature of the measured mode shapes.

(Chance, et al. [56]) found that numerically calculating curvature from mode shapes resulted in unacceptable errors. They used measured strains instead to measure curvature directly, which dramatically improved results.

(Chen and Swamidas [57]), (Dong, et al. [58]), (Kondo and Hamamoto, [59]), and (Nwosu, et al. [60]) present other studies that identify damage and its location from changes in mode shape curvature or strain-based mode shapes.

METHODS BASED ON DYNAMICALLY MEASURED FLEXIBILITY

Another class of damage identification methods uses the dynamically measured flexibility matrix to estimate changes in the static behavior of the structure. Because the flexibility matrix is defined as the inverse of the static stiffness matrix, the flexibility matrix relates the applied static force and resulting structural displacement. Thus, each column of the flexibility matrix represents the displacement pattern of the structure associated with a unit force applied at the associated DOF. The measured flexibility matrix can be estimated from the mass-normalized measured mode shapes and frequencies. The formulation of the flexibility matrix by this method is approximate due to the fact that only the first few modes of the structure (typically the lowest-frequency modes) are measured. The synthesis of the complete static flexibility matrix would require the measurement of all of the mode shapes and frequencies.

Typically, damage is detected using flexibility matrices by comparing the flexibility matrix synthesized using the modes of the damaged structure to the flexibility matrix synthesized using the modes of the undamaged structure or the flexibility matrix from a FEM. Because of the inverse relationship to the square of the modal frequencies, the measured flexibility matrix is most sensitive to changes in the lower-frequency modes of the structure.

Comparison of Flexibility Changes

(Aktan, et al. [61]) propose the use of measured flexibility as a "condition index" to indicate the relative integrity of a bridge. They apply this technique to 2 bridges and compare the measured flexibility to the static deflections induced by a set of truck-load tests.

(Pandey and Biswas [62]) present a damage-detection and -location method based on changes in the measured flexibility of the structure. This method is applied to several numerical examples and to an actual spliced beam where the damage is linear in nature. Results of the numerical and experimental examples showed that estimates of the damage condition and the location of the damage could be obtained from just the first two measured modes of the structure.

(Toksoy and Aktan [63]) compute the measured flexibility of a bridge and examine the cross-sectional deflection profiles with and without a baseline data set. They observe that anomalies in the deflection profile can indicate damage even without a baseline data set.

(Mayes [64]) uses measured flexibility to locate damage from the results of a modal test on a bridge. He also proposes a method for using measured flexibility as the input for a damage-detection method (STRECH) which evaluates changes in the load-deflection behavior of a spring-mass model of the structure.

(Peterson, et al. [65]) propose a method for decomposing the measured flexibility matrix into elemental stiffness parameters for an assumed structural connectivity. This decomposition is accomplished by projecting the flexibility matrix onto an assemblage of the element-level static structural eigenvectors.

(Zhang and Aktan [66]) suggest that changes in curvatures of the uniform load surface (deformed shape of the structure when subjected to a uniform load), calculated using the uniform load flexibilities, are a sensitive indicator of local damage. The authors state that changes in the uniform load surface are appropriate to identify uniform deterioration. A uniform load flexibility matrix is constructed by summing the columns of the measured flexibility matrix. The curvature is then calculated from the uniform load flexibilities using a central difference operator.

Unity Check Method

The unity check method is based on the pseudoinverse relationship between the dynamically measured flexibility matrix and the structural stiffness matrix. An error matrixwhich measures the degree to which this pseudoinverse relationship is satisfied. The relationship uses a pseudoinverse rather than an inverse since the dynamically measured flexibility matrix is typically rank-deficient.

(Lim [67]) proposes the unity check method for locating modeling errors and uses the location of the entry with maximum magnitude in each column to determine the error location. He applies the method to FEM examples and also investigates the sensitivity of the method to non-orthogonality in the measured modes.

(Lim [68]) extends the unity check method to the problem of damage detection. He defines a least-squares problem for the elemental stiffness changes—that are consistent with the unity check error—in potentially damaged members.

Stiffness Error Matrix Method

The stiffness error matrix method is based on the computation of an error matrix that is a function of the flexibility change in the structure and the undamaged stiffness matrix. (He and Ewins [69]) present the stiffness error matrix as an indicator of errors between measured parameters and analytical stiffness and mass matrices. For damage identification, the stiffness matrix generally provides more information than the mass matrix, so it is more widely used in the error matrix method.

(Gysin [70]) demonstrates the dependency of this method on the type of matrix reduction used and on the number of modes used to form the flexibility matrices.The author compared the reduction techniques of elimination, Guyan-reduction, and indirect reduction, and found that the latter two techniques gave acceptable results, while the first technique did not.

(Park, et al. [71]) present a weighted error matrix, where the entries in are divided by the variance in natural frequency resulting from damage in each member. The authors apply their formulation to both beam models and plate models.

Effects of Residual Flexibility

The residual flexibility matrix represents the contribution to the flexibility matrix from modes outside the measured bandwidth so that the exact flexibility matrix can be related to the measured modes and the residual flexibility. (Doebling, et al. [72, 73]) and (Doebling [74]) present a technique to estimate the unmeasured partition of the residual flexibility matrix because only one column of the FRF matrix can be measured for each modal excitation DOF. This technique does not add any new information into the residual flexibility, but it does complete the reciprocity of the residual flexibility matrix so that it can be used in the computation of measured flexibility. The authors demonstrate that the inclusion of the measured residual flexibility in the computation of the measured flexibility matrix yields a more accurate estimate of the static flexibility matrix.

Changes in Measured Stiffness Matrix

A variation on the use of the dynamically measured flexibility matrix is the use of the dynamically measured stiffness matrix, defined as the pseudoinverse of the dynamically measured flexibility matrix. Similarly, the dynamically measured mass and damping matrices can be computed. (Salawu and Williams [75]) use direct comparison of these measured parameter matrices to estimate the location of damage.

(Peterson, et al. [76]) propose a method to use the measured stiffness and mass matrices to locate damage by solving an “inverse connectivity” problem, which evaluates the change in impedance between two structural DOF to estimate the level of damage in the connecting members.

CRITICAL ISSUES FOR FUTURE RESEARCH IN DAMAGE IDENTIFICATION AND HEALTH MONITORING

This section contains a summary of the critical issues, as perceived by the authors, in the field of modal-based structural damage identification and health monitoring. The purpose behind this section is to focus on the issues that must be addressed by future research to make the identification of damage using vibration measurements a viable, practical, and commonly implemented technology.

One issue of primary importance is the dependence on prior analytical models and/or prior test data for the detection and location of damage. Many algorithms presume access to a detailed FEM of the structure, while others presume that a data set from the undamaged structure is available. Often, the lack of availability of this type of data can make a method impractical for certain applications. While it is doubtful that all dependence on prior models and data can be eliminated, certainly steps can and should be taken to minimize the dependence on such information.

Almost all of the damage-identification methods reviewed in this report rely on linear structural models. Further development of methods that have an enhanced ability to account for the effects of nonlinear structural response has the potential to enhance this technology significantly. An example of such a response would be the opening and closing of a fatigue crack during cyclic loading, in either an operational situation or in the case of a forced-vibration test. Many methods are inherently limited to linear model forms and, therefore, cannot account for the nonlinear effects of such a damage scenario. Another advantage of methods that detect nonlinear structural response is that they can often be implemented without detailed prior models. It is of interest to note that the one application where this technology is accepted and commonly used in practice, the monitoring of rotating machinery, relies almost exclusively on the detection of nonlinear response.

The number and location of measurement sensors is another important issue that has not been addressed to any significant extent in the current literature. Many techniques that appear to work well in example cases actually perform poorly when subjected to the measurement constraints imposed by actual testing. Techniques that are to be seriously considered for implementation in the field should demonstrate that they can perform well under the limitations of a small number of measurement locations, and under the constraint that these locations be selected *a priori* without knowledge of the damage location.

An issue that is a point of controversy among many researchers is the general level of sensitivity that modal parameters have to small flaws in a structure. Much of the evidence on both sides of this disagreement is anecdotal because it is only demonstrated for specific structures or systems and not proven in a fundamental sense. This issue is important for the development of health-monitoring techniques because the user of such methods needs to have confidence that the damage will be recognized while the structure still has sufficient integrity to allow repair.

An issue that has received almost no attention in the technical literature is the ability to discriminate changes in the modal properties resulting from damage from those resulting from variations in the measurements resulting from changing environmental and/or test conditions and from the repeatability of the tests: a high level of uncertainty in the measurements will prevent the detection of small levels of damage. Very few modal-based damage detection studies report statistical variations associated with the measured modal parameters used in the damage id process. Even fewer studies report the results of false-positive studies. That is, apply the damage id method to two sets of data from the undamaged structure to verify that the method does not falsely identify damage. Two recent studies (Doebling, et al. [19]) and (Farrar and Jauregui [77]) have started to examine these issues.

With regards to long-term health monitoring of structures such as bridges and offshore platforms, the need to reduce the dependence upon measurable excitation forces is noted by many researchers. The ability to use vibrations induced by ambient environmental or operating loads for the assessment of structural integrity is an area that merits further investigation.

The literature also has scarce instances of studies where different health-monitoring procedures are compared directly by application to a common data set. Some data sets, such as the NASA 8-Bay truss data set and the I-40 Bridge data set, have been analyzed by many different authors using different methods, but the relative merits of these methods and their success in locating the damage have not been directly compared in a sufficiently objective manner. The study of the I-40 Bridge presented in (Farrar and Jauregui [77]) compares five modal-based damage Id methods applied to the same data sets.

Overall, it is the opinion of the authors that sufficient evidence exists to promote the use of measured vibration data for the detection of damage in structures, using both forced-response testing and long-term monitoring of ambient signals. It is clear, though, that the literature in general needs to be more focused on the specific applications and industries that would benefit from this technology, such as health monitoring of bridges, offshore oil platforms, airframes, and other structures with long design life,

life-safety implications and high capital expenditures. Additionally, research should be focused more on testing of real structures in their operating environment, rather than laboratory tests of representative structures. Because of the magnitude of such projects, more cooperation will be required between academia, industry, and government organizations. If specific techniques can be developed to quantify and extend the life of structures, the investment made in this technology will clearly be worthwhile.

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